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INCOHERENT TRANSVERSE TUNE SHIFT CAUSED BY SPACE-CHARGE EFFECTS IN HEPS STORAGE RING AND BOOSTER

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Abstract

In cases of low beam energy and high particle densities, space-charge effects become necessary discussions on transverse beam dynamics. It may cause a big enough tune shift in a circular accelerator moving the beam onto a resonance. In this paper, the transverse tune shift in High Energy Photon Source (HEPS) storage ring and booster ring caused by space-charge effects is firstly estimated based on the existing theory. Since the tune shift is at the level of 0.2, it may move the beam onto a resonance in the operation mode with high bunch charges. Then some simulations are made by tracking particles with elegant in the HEPS storage ring and booster including the space-charge effects. During the tracking, some particles are lost in HEPS booster ring with bunch charge of 14.4nC for the so called "swap-out" mode. Further simulation shows that no particles would be lost if the charge of single bunch was less than 8.6nC in HEPS booster.

INTRODUCTION

The High Energy Photon Source (HEPS), with a beam energy of 6 GeV, a natural emittance of 59.4 pm·rad and a storage ring circumference of 1295.6m, is a diffraction-limited storage ring to be built in Beijing [1]. The beam current is 200mA, and currently two filling patterns are under consideration. One is the high brightness mode with 648 bunches and the other one is the timing mode with 60 bunches.

The space-charge effect forces the beam to defocus transversely to produce tune shift, which may cause the particles to cross the resonance lines during the accumulation and acceleration process, resulting in loss of the beam or deterioration of the beam quality. Although space-charge effects is often overlooked in the discussion of high-energy accelerators, it must be taken into account in the case of low energy and high particle density. Considering the ultra-low-emittance and the mode of 60 bunches with single bunch charge 14.4 nC in HEPS storage ring, space-charge effects may result in deterioration of the beam quality. Also, the booster is ramping from low energy 300 MeV, and the single bunch charge is large with "swap-out" mode, space-charge effects may result in loss of the beam. So we study the transverse tune shift in HEPS storage ring and booster ring caused by space-charge effects.

In this paper, based on current parameters [2], the transverse tune shift in HEPS storage ring and booster ring caused by space-charge effects is firstly estimated based on the existing theory. Some simulations are made by tracking particles with elegant [3] in HEPS storage ring and booster ring including the space-charge effects.

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TUNE SHIFT THEORY

Due to the nonuniform charge distribution within a beam, tune shifts are not the same for all particles. Only particles close to the beam center suffer the maximum tune shift, but less affect betatron oscillation amplitudes. The space-charge effects therefore introduces a tune spread rather than a coherent tune shift and we refer to this effect as the incoherent space-charge tune shift.

The incoherent space-charge tune shift is [4]

$$\Delta\nu_{x,y} = -\frac{\lambda r_c}{(2\pi)\beta^2\gamma^3}\left[\oint \frac{\beta_{x,y}}{\sigma_{x,y}(\sigma_x+\sigma_y)}dz + 2(1+\beta^2\gamma^2 B)\int_0^{L_{vac}} \frac{\varepsilon_1\beta_{x,y}}{b^2}dz 2\beta^2\gamma^2 B\int_0^{L_{mag}} \frac{\varepsilon_2\beta_{x,y}}{g^2}dz\right] \quad (1)$$

where $\lambda = \frac{N_{tot}}{n_b l_b} = \frac{N_{tot}}{n_b\sqrt{2\pi}\sigma_l}$ is the linear particle density, N_{tot} is the total number of particle in the circulating beam, n_b is the number of bunches, σ_l is the standard bunch length for a Gaussian distribution, $r_c = \frac{q^2}{4\pi\epsilon_0 mc^2}$ is the classical particle radius, $\sigma_{x,y}$ is the beam size, $B = \frac{n_b l_b}{2\pi R}$ is the bunch occupation along the ring circumference, b is the vertical half axis of an elliptical vacuum chamber, a is the horizontal half axis, as shown in Fig. 1, ε_1 and ε_2 are the Laslett form factors, $\varepsilon_2 = \frac{\pi^2}{24}$, ε_1 is compiled in Table 1.

Table 1: Laslett Incoherent Tune Shift form Factors for Elliptical Vacuum Chamber[4,5]

a/b	1	6/5	5/4	4/3	3/2	2/1	∞
ε_1	0	0.065	0.09	0.107	0.134	0.172	$\frac{\pi^2}{48}$

In equation (1), the loop integral is equal to the total length of the ring, the integration length L_{vac} is equal to the total length of the vacuum chamber, L_{mag} is the total length of magnets along the ring circumference.

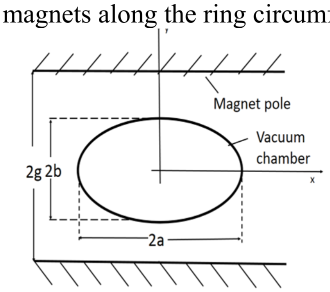

Figure 1: Metallic vacuum chamber and ferromagnetic boundaries.

TUNE SHIFT IN STORAGE RING

The main parameters of the HEPS storage ring used for

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space chare effect calculation are listed in Table 2. The natural emittance and the circumference are 59.4 pm·rad and 1295.6 m, respectively. The radius of circular vacuum chamber is 11mm in HEPS storage ring with $\varepsilon_1 = 0$, $\varepsilon_2 = \frac{\pi^2}{24}$.

Table 2: Main Parameters of the HEPS Storage Ring [2]

Parameter	Symbol,unit	HEPS
Beam energy	E, GeV	6
Beam current	I_0, mA	200
Bunch number	n_b	648/60 *
Bunch population	N	8.33e9/9e10
Bunch current	I_b, mA	0.3/3.3
Bunch length	σ_z, mm	3
Emittance	$\varepsilon_x/\varepsilon_y$, pm·rad	59.4/5.94
Betatron tune	ν_x/ν_y	116.16/41.12

*For the mode of 648 bunches, single bunch population is 8.33e9 and single bunch charge is 1.33 nC; for the mode of 60 bunches, single bunch population is 9e10 and single bunch charge is 14.4 nC.

The calculation of incoherent space-charge tune shift is listed in Table 3. The range of incoherent tune shift with 648 bunches and 60 bunches in resonance lines diagram are shown in Fig. 2. Note that the incoherent tune shift with 648 bunches is far from the resonance lines, however, the incoherent tune shift with 60 bunches cross the resonance lines. So we studied the case of 14.4nC bunch charge for the mode of 60 bunches with elegant [3].

Table 3: The Calculation of Incoherent

	Tune shift	Bunch number	
HEPS		648	60
6GeV	$\Delta\nu_x$	-3.2e-3	-0.035
	$\Delta\nu_y$	-1.82e-2	-0.196

Particles are tracked through a zero length multipole to simulate space charge effects in elegant [3]. 10000 particles are tracked with only the space-charge effects for 10000 turns, and no particles are lost. We recorded each of particle coordinates, then processed frequency of each particle by using Fourier Transforms. The particle statistics of tune shift caused by space-charge effects in the horizontal and vertical direction are shown in Fig 3. The average value of $\Delta\nu_x$ is –0.0343, and the average value of $\Delta\nu_y$ is –0.164. It can be seen that the simulation results are consistent with the calculated results (Table 3).

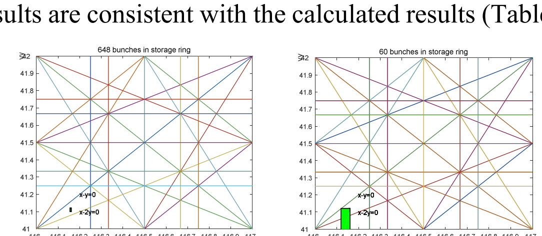

Figure 2: The range of incoherent tune shift with 648 bunches and 60 bunches in resonance lines diagram.

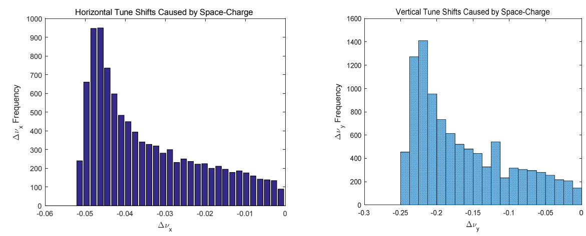

Figure 3: The particle statistics of tune shift caused by space-charge effects in the horizontal (x) and vertical direction (y), respectively.

TUNE SHIFT IN BOOSTER

The main parameters of the HEPS booster used for space chare effect calculation are listed in Table 4. The circumference is 431.77 m. The vertical and horizontal half axis of elliptical vacuum chamber are 12.5mm and 15mm in HEPS booster, with $\varepsilon_1 = 0.065$, $\varepsilon_2 = \frac{\pi^2}{24}$.

Table 4: Main Parameters of the Booster [2]

Parameter	Symbol, unit	Low energy	High energy
Beam energy	E, GeV	0.3	6
Beam current	I_0, mA	15	15
Bunch number	n_b	30	30
Bunch current	I_b, mA	0.5	0.5
Bunch population	N	4.5e9	4.5e9
Bunch length	σ_z, mm	30	10
Emittance	$\varepsilon_x/\varepsilon_y$,nm·rad	70/70	4.1/0.4
Betatron tune	ν_x/ν_y	26.3/8.13	

The calculation of incoherent tune shift with 300MeV and 6GeV are listed in Table 5. The range of incoherent tune shift with 300MeV is shown in Fig.4. Fig 5 shows the change of tune shift with ramping in booster. Note that the incoherent tune shift with 300MeV is far from the resonance lines, then we studied incoherent tune shift for the “swap out” mode.

Table 5: The Calculation of Incoherent Tune Shift with 300MeV and 6GeV in Booster

	Tune shift	N=4.5e9
300MeV	$\Delta\nu_x$	-5.1e-4
	$\Delta\nu_y$	-7.1e-4
6GeV	$\Delta\nu_x$	-1.49e-5
	$\Delta\nu_y$	-2.91e-5

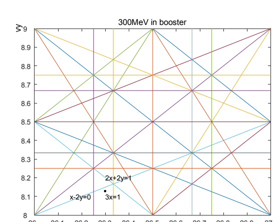

Figure 4: The range of incoherent tune shift with 300MeV in resonance lines diagram.

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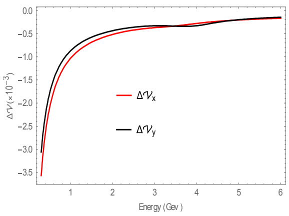

Figure 5: the change of tune shift with ramping in booster.

In the "swap-out" mode [1], the bunch charge of Booster is the same as that of the storage ring. Other parameters and simulations are the same as Table 4. The calculation of incoherent tune shift with 300MeV and 6GeV are listed in Table 6. The range of incoherent tune shift with 300MeV for "swap-out" mode with 14.4 nC single bunch charge is shown in Fig. 6. The change of tune shift with ramping in booster with 14.4 nC bunch charge are shown in Fig. 7. The particle statistics of tune shift caused by space-charge effects in the horizontal and vertical direction with 14.4nC bunch charge are shown in Fig 8. The average value of $\Delta\nu_x$ is –0.015, and the average value of $\Delta\nu_y$ is –0.0145. It can be seen that the simulation results are consistent with the calculated results (Table 6). However, some particles are lost in the case of 14.4nC bunch charge. This may be the result of some particles reaching the vertical aperture in the case of large charge and low energy. No particles would be lost if the charge of single bunch was less than 8.6nC in HEPS booster.

Table 6: The Calculation of Incoherent Tune Shift for "swap-out" Mode in Booster

	Tune shift	N=8.33e9 (1.33nC)	N=9e10 (14.4nC)
300MeV	$\Delta\nu_x$	-9.44e-4	-1.02e-2
	$\Delta\nu_y$	-1.3e-3	-1.42e-2
6GeV	$\Delta\nu_x$	-2.76e-5	-2.98e-4
	$\Delta\nu_y$	-5.39e-5	-5.82e-4

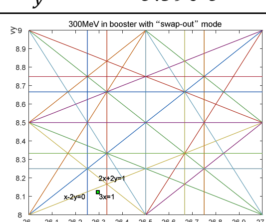

Figure 6: The range of incoherent tune shift with 300MeV for "swap-out" mode with 14.4 nC single bunch charge.

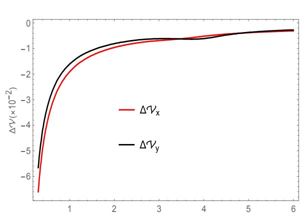

Figure 7: The change of incoherent tune shift with ramping in booster with 14.4 nC single bunch charge.

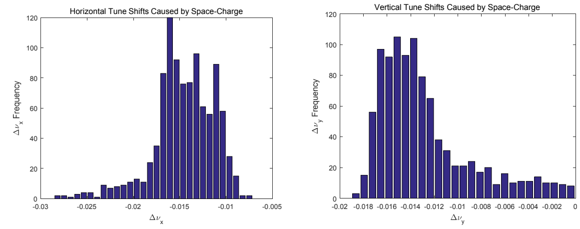

Figure 8: The particle statistics of tune shift caused by space-charge effects in the horizontal and vertical direction with14.4nC bunch charge, respectively.

CONCLUSION

Since the vertical tune shift is at the level of 0.2 in the operation mode with 14.4nC bunch charge, it move the beam onto a resonance. However, it does not affect the beam from the results of particle tracking, the tune shift of simulation results are also consistent with that of calculated results. I suggest that stretch beam length and adjust the tune shift. Moreover, we calculate the change of tune shift with ramping in booster. In the "swap-out" mode, the tune shift of simulation results are also consistent with that of calculated results with 14.4nC bunch charge at 300MeV. However, some particles are lost. This is the result of some particles reaching the vertical aperture in the case of large charge and low energy, the reason of reaching the vertical aperture is under discussion. I suggest that bunch charge should be less in the case of low beam energy. After simulating different bunch charge, no particles would be lost if the charge of single bunch was less than 8.6nC in HEPS booster.

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